241.92-Bit/s/Hz Spectral-Efficiency Transmission over 14-km 7-Core Ring Core Fiber with Low-Complexity 4 × 4 MIMO Equalization

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Abstract: The transmission of 84 OAM modes with spectral efficiency of 241.92 bit/s/Hz over 14 km 7-core ring core fiber whose cladding diameter is 180μm is demonstrated, using 4 × 4 MIMO equalizations.

1. Introduction

With the development of existing single-mode optical fiber communication technology over decades, the capacity per single mode fiber (SMF) is approaching the physical limit defined by nonlinear Shannon limit [1]. To break such capacity limit, space division multiplexing (SDM) systems have received numerous attentions in recent years. By making fuller utilization of the fiber cross-sectional area, SDM systems rapidly drive the capacity growth by multiplexing more mode/spatial channels in one fiber [2-4]. However, as the number of multiplexed mode/spatial channels increases, the complexity of multiple-input multiple-output (MIMO) equalization used to deal with inter-mode crosstalk and differential mode delay (DMD) will rapidly climb [5].

To reduce the MIMO complexity, SDM systems based on weakly-coupled few-mode multicore fiber (FM-MCF) have been proposed, where only partial MIMO processing is required to deal with the crosstalk among the modes that propagate in the same core while the ultra-low crosstalk among different fiber cores can be neglected. The number of modes transmitted within one fiber core has been limited to keep the low complexity of partial MIMO equalization. The capacity of such systems can be increased by incorporating more fiber cores. This will however enlarge the fiber cladding diameter (to more than $200\mu m$), degrading the performance in fiber fabrication, splicing and reliability [2,4]. Alternatively, the number of modes in each core can be increased to achieve higher capacity with low MIMO complexity, as long as they can be partitioned into degenerate mode groups that ae also sufficiently weakly coupled with each other, to enable partial MIMO within each MG without the need for MIMO across the entire mode-set.

Recently, SDM systems based on ring-core fibers have received sustained attention due to their good scalability toward high-order mode space [6-8]. SDM system based on multi-core ring-core fibers (MC-RCFs) with the capacity over 1Pbit/s using low-complexity 4 × 4 MIMO equalization has been reported [9], achieving a row (net) spectral efficiency (SE) of 156.8 (130.7) bit/s/Hz.

In this paper, for the first time, the MC-RCFs based SDM transmission system with a net spectral efficiency over 200 bit/s/Hz is successfully demonstrated. In this transmission system, 84 OAM mode channels (7 cores × 6 OAM modes × 2 polarizations) are transmitted over a 14-km 7-core RCF with the cladding diameter of 180μm. In each mode channel, 40 wavelength-division multiplexing (WDM) channels with 12.5 GHz grid, each carrying 12-Gbaud 8-quadrature amplitude modulation (8QAM) signals, are transmitted. Finally, a raw (net) SE of 241.92 (201.6) bit/s/Hz and a capacity of 120.96(100.8) Tbps with the bit-error rate (BER) below the 20% soft decision forward error correction (FEC) threshold of 2.4×10^{-2} is achieved, only using modular 4 × 4 MIMO equalization with the tap number no more than 15.

2. Experimental setup

The experimental setup of the OAM-WDM-SDM transmission system is shown in Fig. 1. At the transmitter, due to limited device resources, sliding test channels with high optical signal-to-noise ratio (OSNR) and dummy channels with low OSNR are multiplexed together to generate 40 WDM carriers. 5 optical carriers with wavelengths in a 0.1nm/12.5 GHz grid from external cavity lasers (ECLs) are used as sliding test bands. The light source of the dummy wavelength band comes from a WDM carrier generator based on multiple seed light sources modulated by a cascaded phase modulator and Mach-Zehnder modulator (MZM). Then the test and dummy bands are combined by a wavelength division multiplexer and then modulated by 12-Gbaud 8QAM signals from an arbitrary waveform generator (AWG) through an in-phase/quadrature (I/Q) modulator to form the 40-channel WDM signals ranging from 1548.16 nm to 1552.16 nm with 0.1nm/12.5 GHz grid.

The generated WDM signals are equally divided into four branches via a power splitter and then amplified by EDFAs. Three of them are used to generate mode channels with high OSNR in the fiber core under test, while the other one is further split and used to implement low OSNR channels in the dummy cores. Following that, the generated test and dummy mode/spatial channels are injected into six hexagonally packed 7-core SMFs spliced with fan-in devices, and the Gaussian-like beams from the 7-core SMF are collimated, linear polarization filtered and finally imaged to the spatial light modulator (SLM) to form OAM beams with topological charge $+l$ or $-l$ (l = 2, 3, 4) by the phase mask. The generated linearly-polarized OAM beams with topological charge l =±2, ±3 and ±4 are combined by three beam combiners (BSs), and then converted into circular polarizations using a quarter-wave plate (QWP). After propagating through the polarization multiplexing module, which is composed of a polarization beam splitter (PBS), an optical de-correlation path with a 4-f configuration and a polarization beam combiner (PBC), four OAM modes <+l, R>, <+l, L>, <−l, R> and <−l, L> are generated in each mode group (MG). After that, the OAM beams are converted into circular polarizations and coupled into a 14-km 7-core RCF. Then the OAM spatial beams emitted from the 7-core RCF are split into two branches, each of which is converted into a Gaussian beam by the vortex phase plate (VPP) with an opposite topological charge and finally coupled into a SMF-pigtailed dual-polarization integrated coherent receiver (ICR). On the receiver side, due to the limited device resource, only one MG including 4 OAM modes in the tested fiber core are de-multiplexed and go through 4×4 MIMO equalization to deal with the intra-MG crosstalk simultaneously. Signals from different OAM MGs/cores are de-multiplexed and tested one by one.

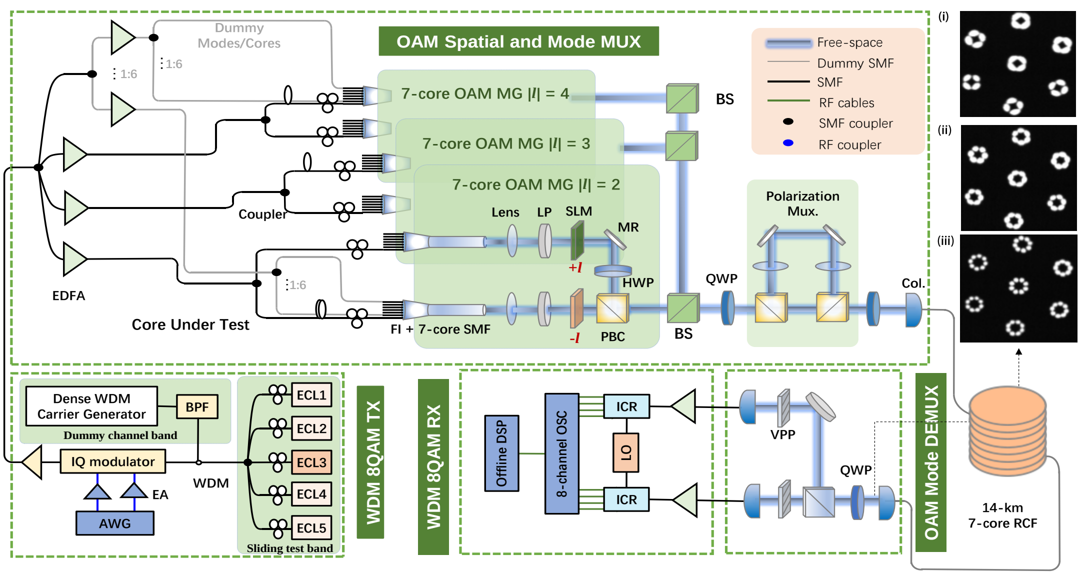

Fig. 1 Experimental setup. ECL: external cavity laser; AWG: arbitrary waveform generator; EDFA: erbium doped fiber amplifier; EA: electrical amplifier; MR: mirror; LP: linear polarizer; SLM: spatial light modulator; PBC: polarization beam combiner; HWP: half-wave plate; PBS: polarization beam splitter; QWP: quarter-wave plate; BS: beam splitter; Col.: collimator; VPP: vortex phase plate; ICR: integrated coherent receiver.

The eight electrical signals from two ICRs are sampled and stored by an eight-channel real-time oscilloscope at a sampling rate of 80-GSa/s. Finally, Offline DSP is performed, including timing phase recovery, 4×4 MIMO equalization based on the constant modulus algorithm, frequency offset estimation and carrier phase estimation.

3. Results

The measured BERs of all 3360 channels (7 cores × 6 OAM modes × 2 polarizations × 40 WDM channels) is shown in Fig. 2(a). All of them are below the 20% soft-decision FEC threshold correcting BER of 2.4×10^{-2}. As the BER evaluation of two orthogonal polarizations of each OAM mode is implemented together, only two values are illustrated in each MG. Because of the crosstalk from two adjacent MGs (|l| =2, 4), the BER performance of MG with topological charge |l| = 3 is worse than the other two MGs. Fig. 2(b) shows the constellations of recovered signals of the 6 OAM modes in the central fiber core at 1550.66 nm. And Fig. 2(c) depicts the corresponding tap weights of MG with topological charge |l| = 4 in the central fiber core after 30 iterations of updating by CMA. The number of time-domain equalization taps is set to 15 to cover the DMD. The complexity of MIMO equalization could be further decreased by performing in frequency domain.

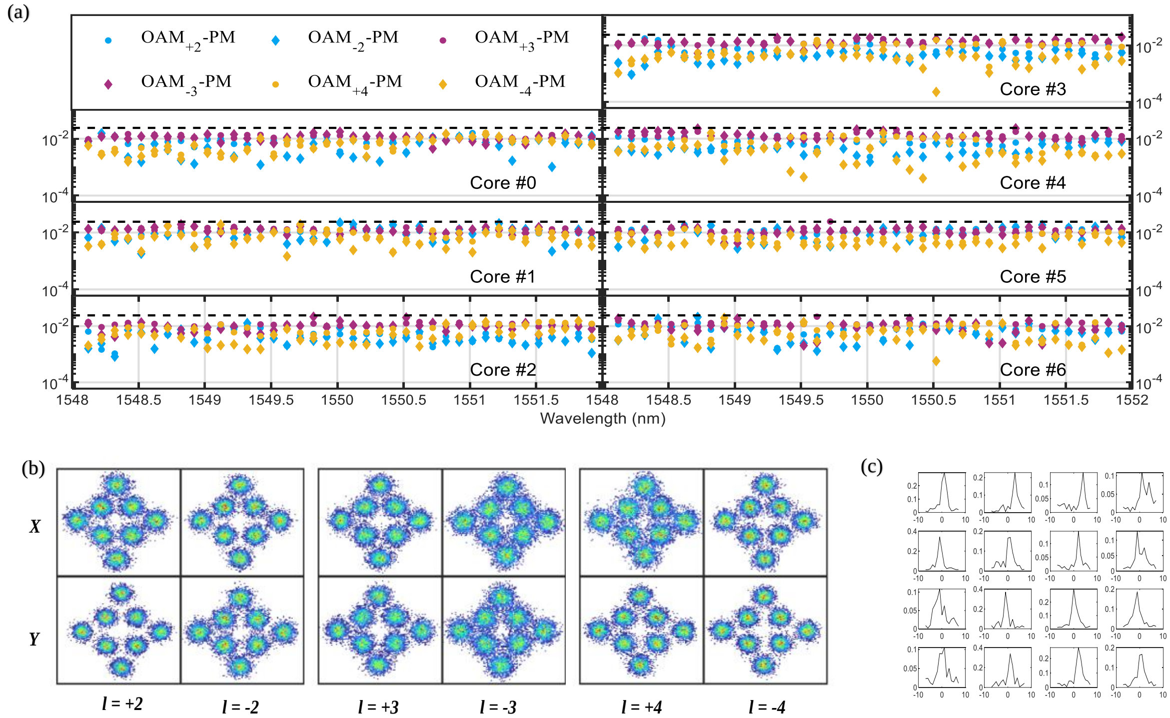

Fig. 2 (a) Measured BER of all 3360 channels after 14 km 7-core RCF transmission; (b) The constellations of 6 modes in the center core.; (c) MIMO tap weights of the MG with topological charge $|l| = 4$

4. Conclusion

An OAM-SDM-WDM transmission system over a 14-km 7-cores RCF with $180\mu m$ cladding diameter has been experimentally demonstrated. By transporting 3360 channels each with 12-Gband 8QAM signals, a raw (net) capacity of 120.96(100.8) Tbps and a SE of 241.92 (201.6) bit/s/Hz is achieved in this system, only requiring modular 4×4 equalizations with tap number of 15.

5. Acknowledgements

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